(12) **United States Patent** (10) **Patent No.:** **US 9,459,362 B2**
Laws   (45) **Date of Patent:**   **Oct. 4, 2016**

(54) **MARINE VIBRATOR SWEEPS WITH REDUCED SMEARING AND/OR INCREASED DISTORTION TOLERANCE**

(75) Inventor: **Robert Laws**, Cambridge (GB)

(73) Assignee: **WESTERNGECO L.L.C.**, Houston, TX (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 284 days.

(21) Appl. No.: **14/003,775**

(22) PCT Filed: **Mar. 12, 2012**

(86) PCT No.: **PCT/IB2012/051154**

§ 371 (c)(1),
(2), (4) Date: **Sep. 6, 2013**

(87) PCT Pub. No.: **WO2012/123884**

PCT Pub. Date: **Sep. 20, 2012**

(65) **Prior Publication Data**

US 2013/0343153 A1   Dec. 26, 2013

Related U.S. Application Data

(60) Provisional application No. 61/452,356, filed on Mar. 14, 2011.

(51) **Int. Cl.**
G01V 1/38   (2006.01)
G01V 1/28   (2006.01)

(52) **U.S. Cl.**
CPC *G01V 1/3808* (2013.01); *G01V 1/28* (2013.01); *G01V 1/38* (2013.01); *G01V 1/3861* (2013.01)

(58) **Field of Classification Search**
CPC G01V 1/3808; G01V 1/38; G01V 1/28; G01V 1/3861

USPC 367/15, 21
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

4,598,392	A	*	7/1986	Pann	.... G01V 1/005
					367/189
4,782,446	A		11/1988	Ehler et al.	
5,410,517	A	*	4/1995	Andersen	.... G01V 1/375
					181/108
6,041,018	A	*	3/2000	Roche	.... G01V 1/366
					340/853.1
6,049,507	A		4/2000	Allen	
6,151,556	A		11/2000	Allen	
6,152,256	A		11/2000	Favret et al.	
6,942,059	B2		9/2005	Smith	
7,966,134	B2	*	6/2011	German	.... G01N 3/30
					702/33
2001/0020218	A1		9/2001	Cosma	

(Continued)

FOREIGN PATENT DOCUMENTS

CN	103443655 A	12/2013
WO	2012123883	9/2012

OTHER PUBLICATIONS

International Search Report and Written Opinion of PCT Application No. PCT/IB2012/051153 dated Oct. 19, 2012: pp. 1-11.

(Continued)

Primary Examiner — Daniel L Murphy
(74) *Attorney, Agent, or Firm* — Kevin B. McGoff

(57) **ABSTRACT**

A marine seismic survey using one or more moving marine seismic vibrators, where the vibrator sweeping function is based on smearing error criteria and is a downward-sweeping non-linear sweep function. The acquired seismic data can either be used as is without desmearing or desmeared easily.

21 Claims, 11 Drawing Sheets
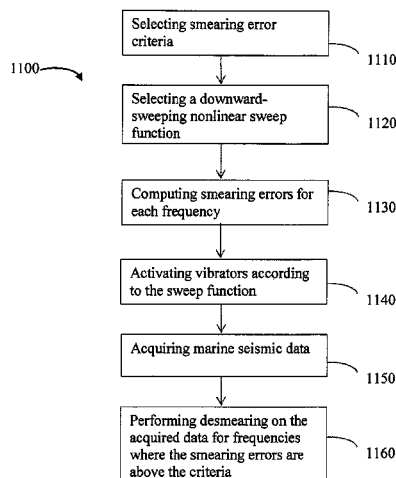
(56)   **References Cited**

U.S. PATENT DOCUMENTS

2004/0089499	A1	5/2004	Smith	
2004/0228214	A1*	11/2004	Tulett	G01V 1/3861
				367/15
2005/0243648	A1*	11/2005	Kinkead	G01V 1/362
				367/52
2007/0133354	A1*	6/2007	Bagaini	G01V 1/005
				367/189
2009/0076730	A1	3/2009	Johnson et al.	
2010/0195434	A1	8/2010	Menger et al.	

OTHER PUBLICATIONS

International Search Report and Written Opinion of PCT Application No. PCT/IB2012/051154 dated Oct. 18, 2012: pp. 1-9.

Houston et al., "OTC 5641: A Marine Digital Vibrator: Part II—Implementation," 20th Annual Offshore Technology Conference, May 1988: pp. 223-226.
Laws et al., "B026: Are Seismic Sources Too Loud?" 70th EAGE Conference & Exhibition, Jun. 2008: pp. 1-5.
"LGL Report TA4604-1: Environmental Assessment of Marine Vibroseis," LGL Ltd., environmental research associates and Marine Acoustics Inc., Apr. 2011: pp. 1-227.
Southall et al., "Marine Mammal Noise Exposure Criteria: Initial Scientific Recommendations," Aquatic Mammals, 2007, vol. 33(4): pp. 411-521.
Office Action issued in corresponding Chinese Application No. 201280018543.5 mailed Aug. 28, 2015 (10 pages).
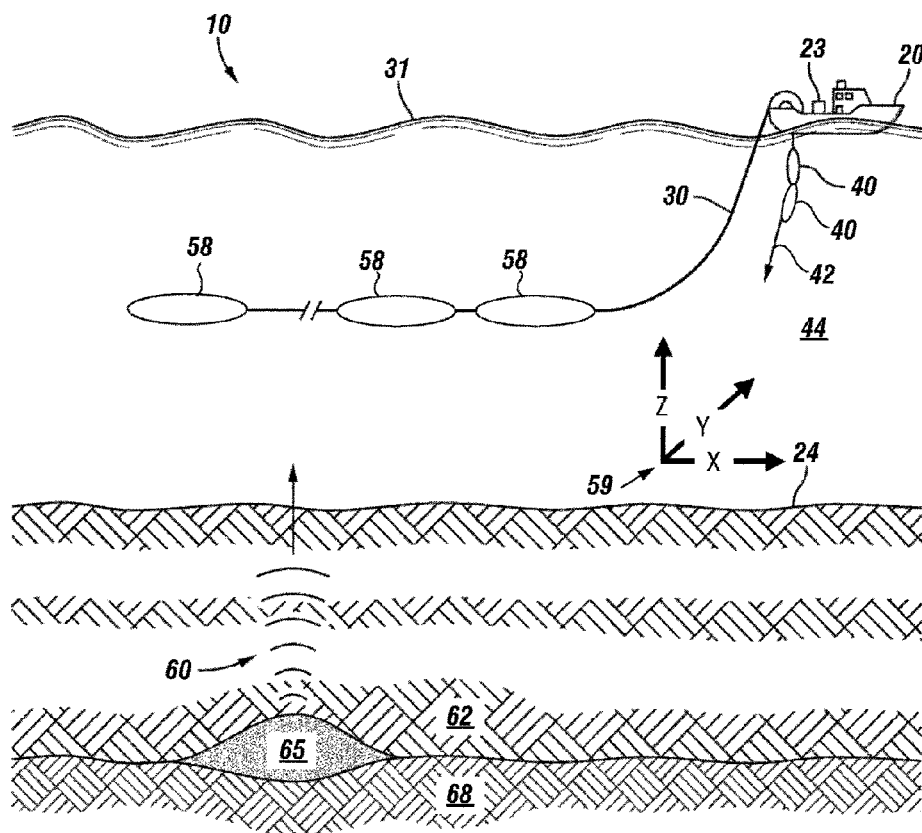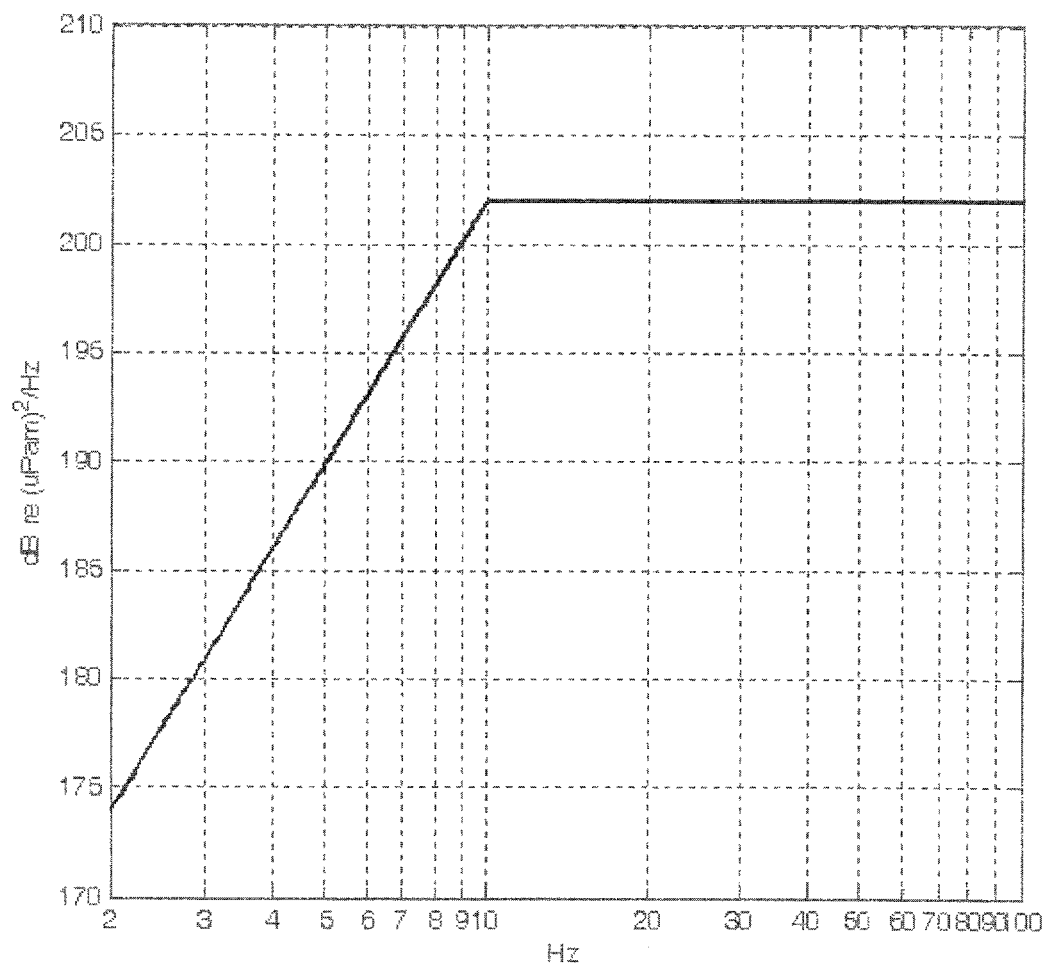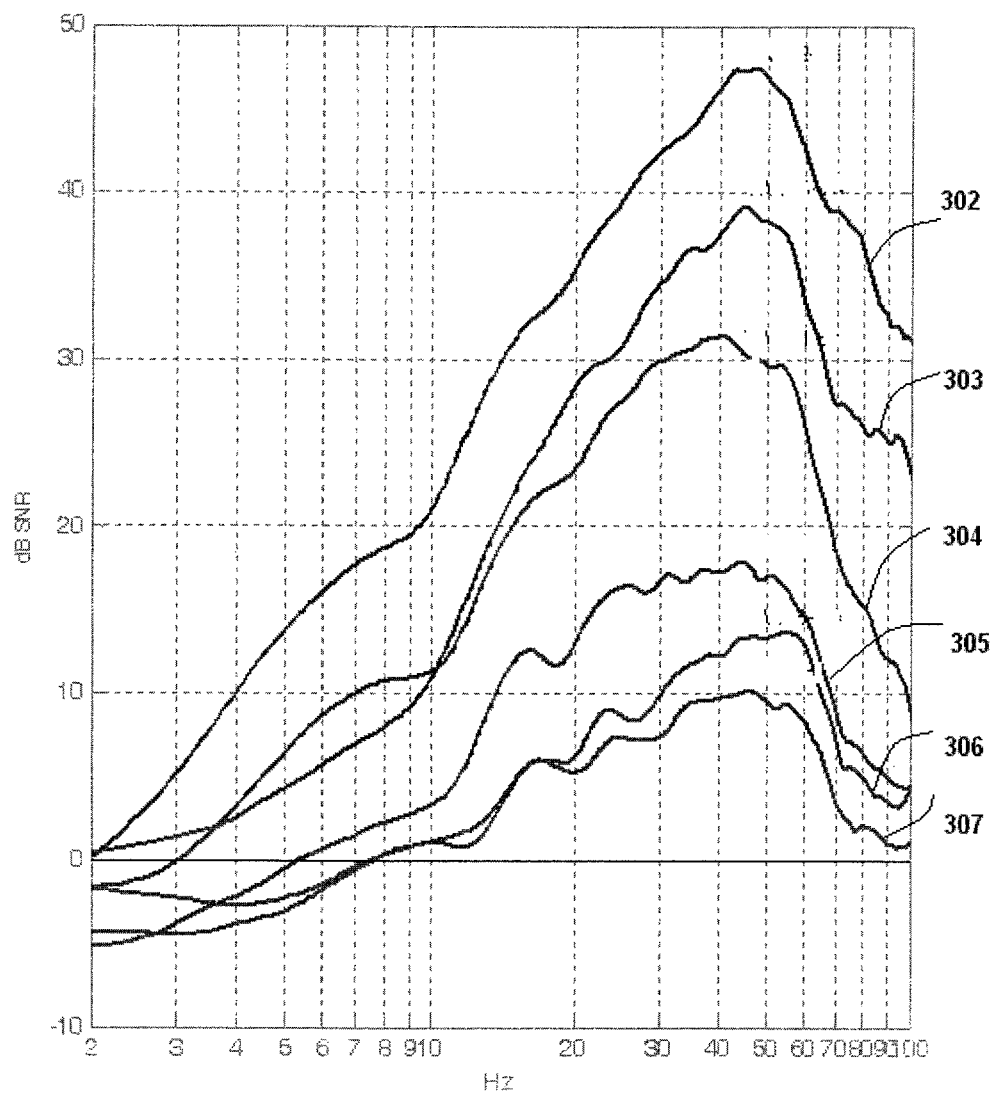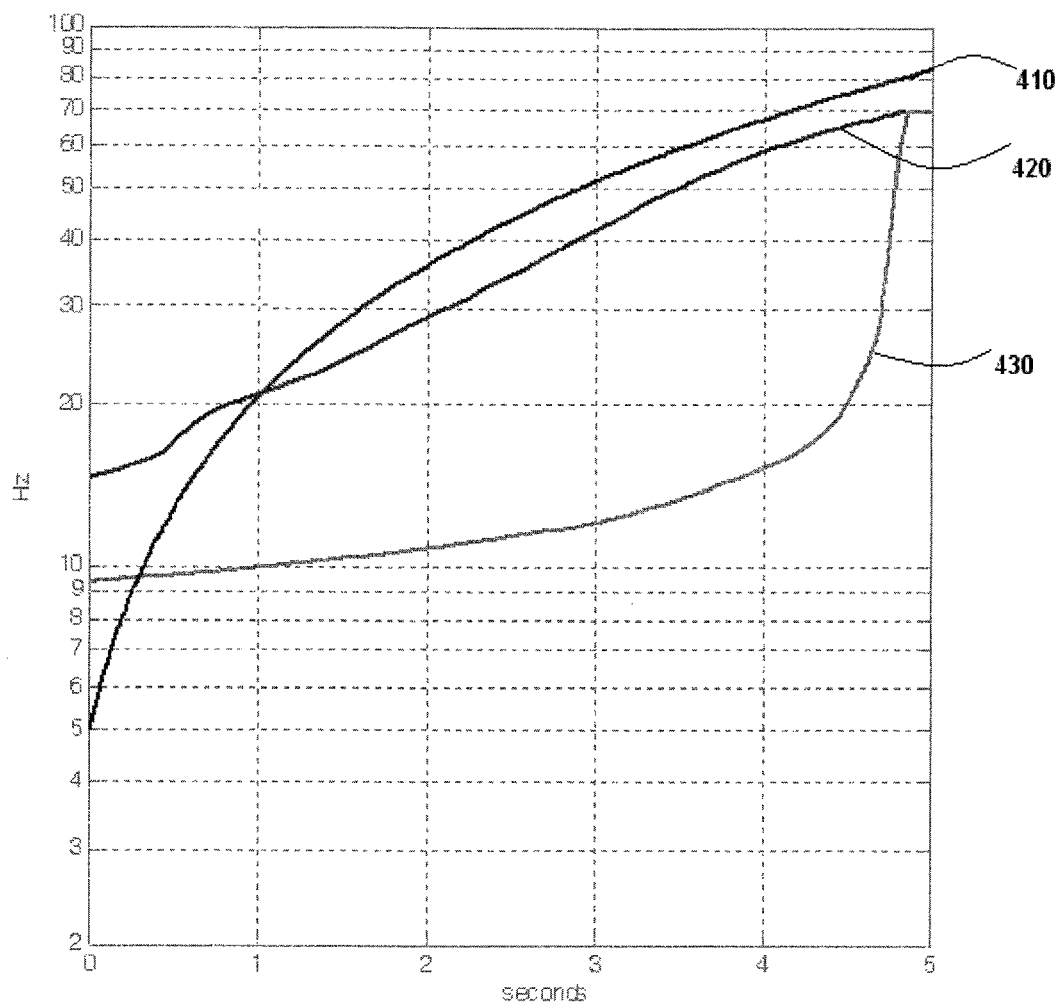
* cited by examiner

FIG. 1

FIG. 2

FIG. 3

FIG. 4

FIG. 5

600

635   633   631

629

630

627

625   626

FIG. 6

700

Obtaining a quality requirement   710

Setting a sweep function based
on the requirement   720
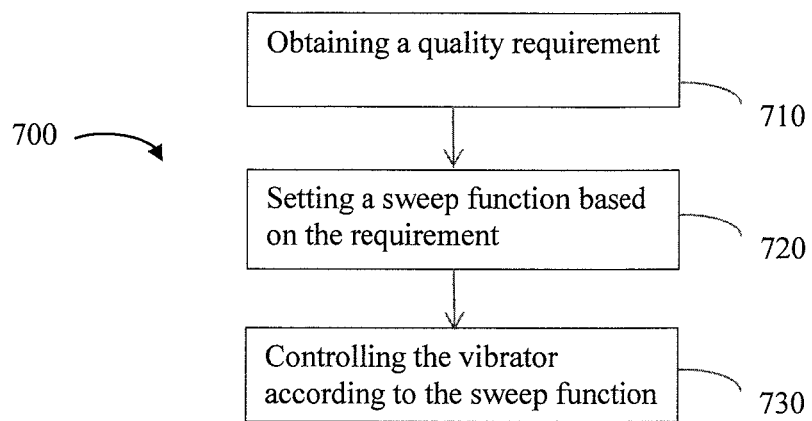
Controlling the vibrator
according to the sweep function   730

FIG. 7

FIG. 8

FIG. 9

FIG. 10

1100

| Selecting smearing error criteria | 1110 |

↓

| Selecting a downward-sweeping nonlinear sweep function | 1120 |

↓

| Computing smearing errors for each frequency | 1130 |

↓

| Activating vibrators according to the sweep function | 1140 |

↓

| Acquiring marine seismic data | 1150 |

↓

| Performing desmearing on the acquired data for frequencies where the smearing errors are above the criteria | 1160 |

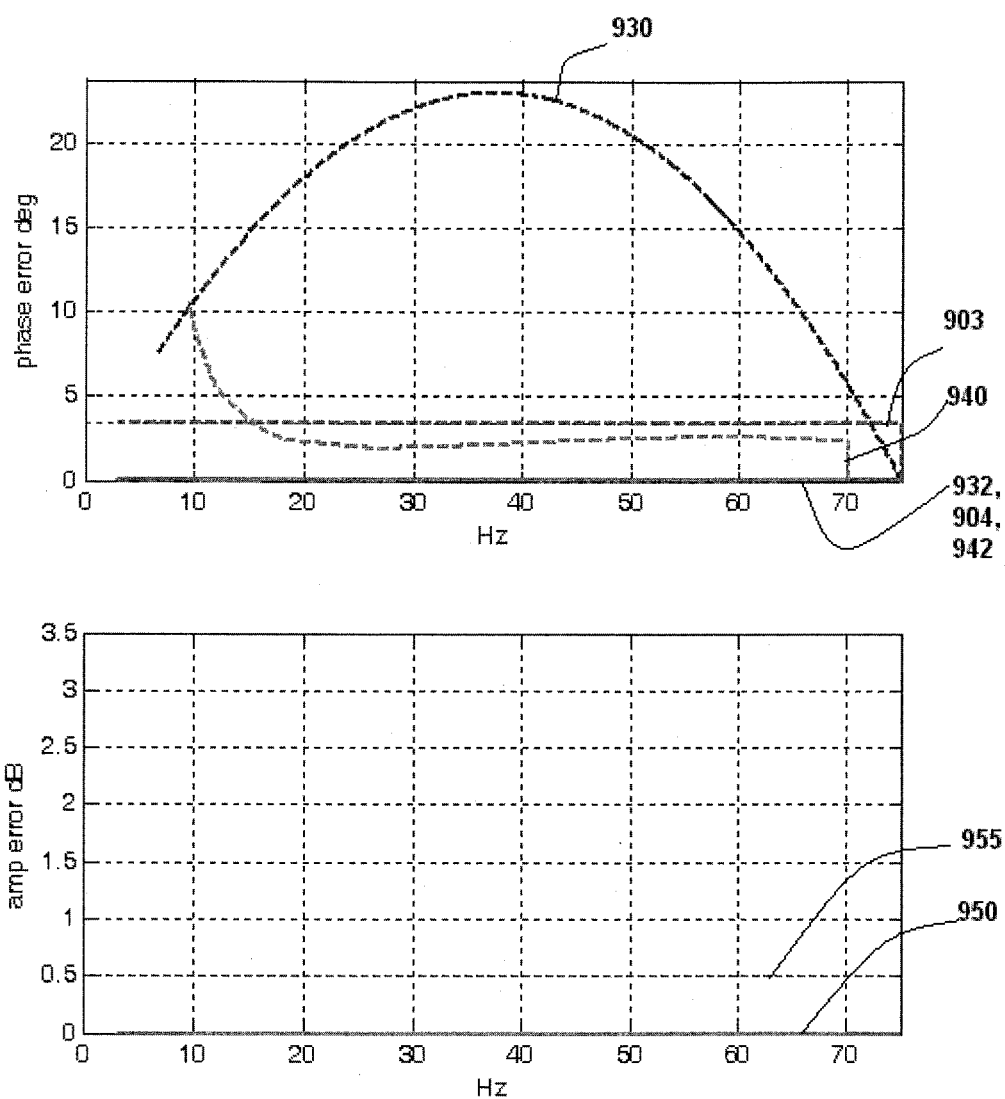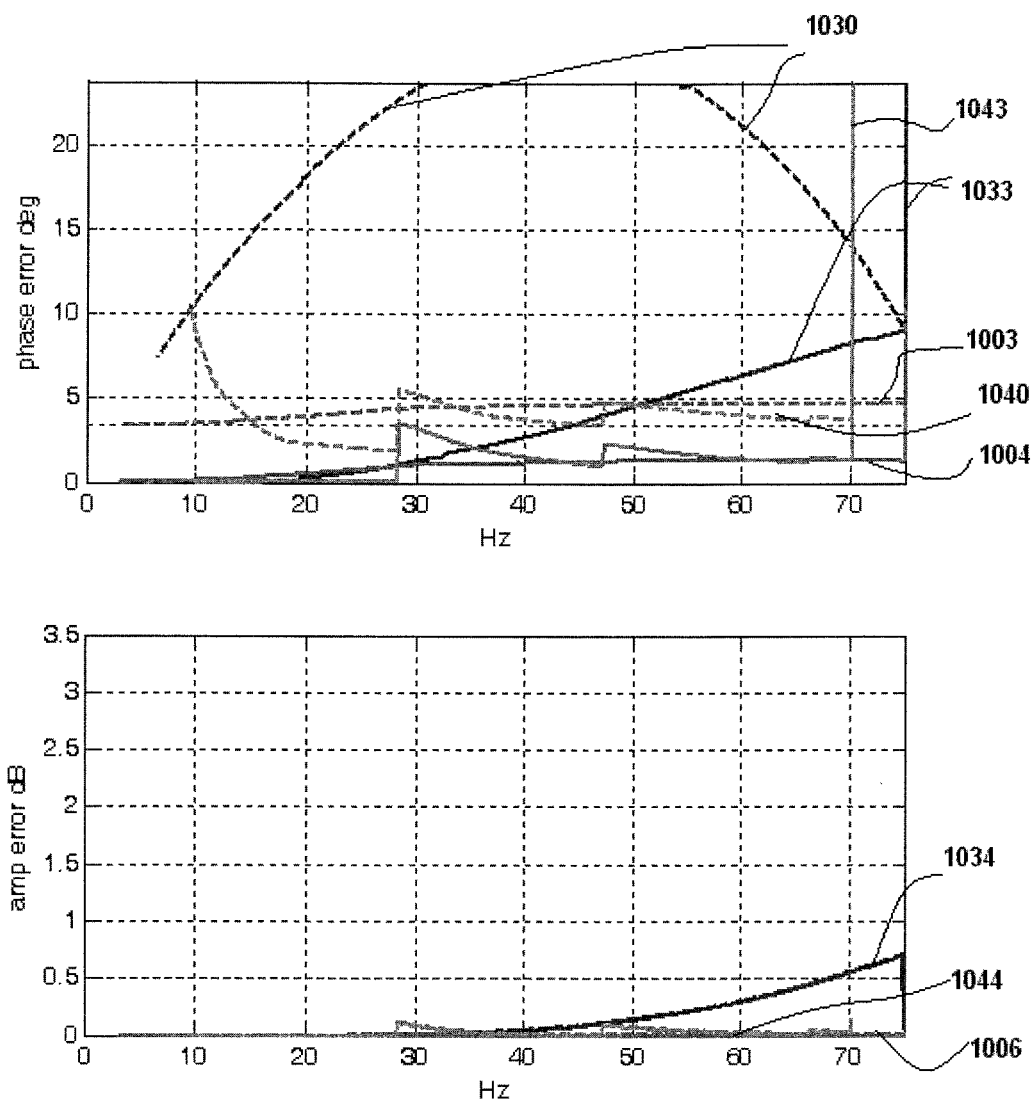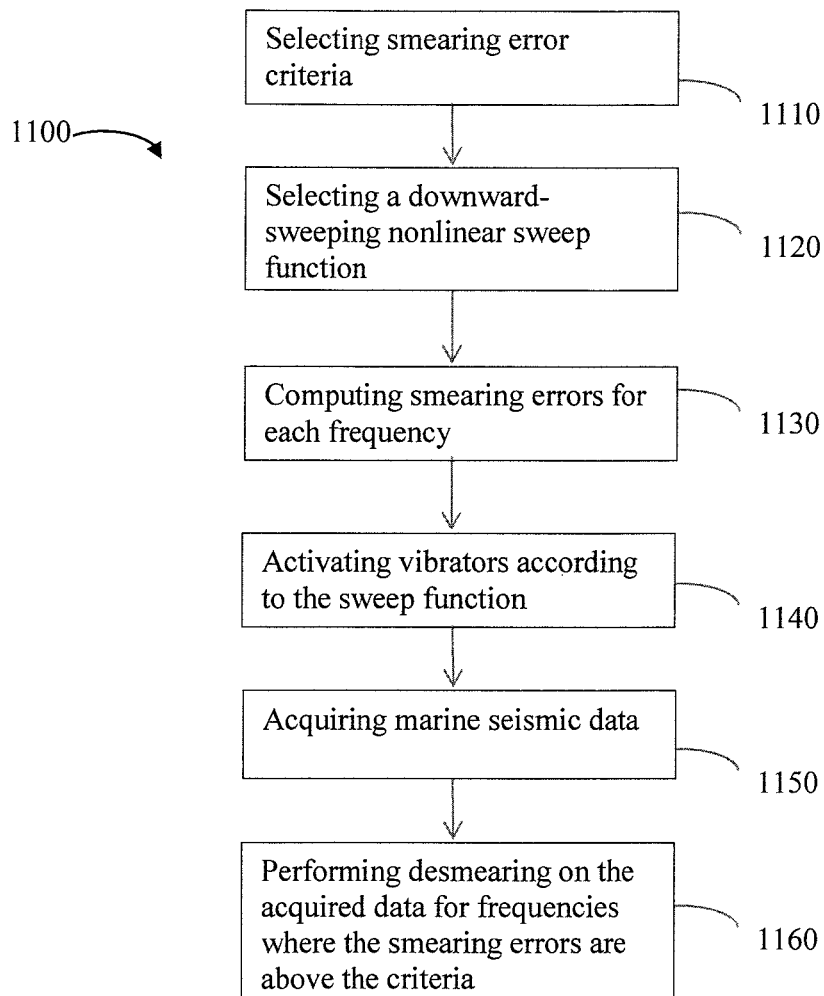**FIG. 11**

MARINE VIBRATOR SWEEPS WITH REDUCED SMEARING AND/OR INCREASED DISTORTION TOLERANCE

BACKGROUND

This disclosure relates to seismic exploration for oil and gas and, in particular but not by way of limitation, relates to marine seismic survey using marine vibrators with reduced smearing or increased tolerance of distortion.

Seismic exploration involves surveying subterranean geological formations for hydrocarbon deposits. A survey may involve deploying seismic source(s) and seismic sensors at predetermined locations. The sources generate seismic waves, which propagate into the geological formations, creating pressure changes and vibrations along the way. Changes in elastic properties of the geological formation scatter the seismic waves, changing their direction of propagation and other properties. Part of the energy emitted by the sources reaches the seismic sensors. Some seismic sensors are sensitive to pressure changes (hydrophones), and others are sensitive to particle motion (e.g., geophones); industrial surveys may deploy one type of sensor or both types. In response to the detected seismic events, the sensors generate electrical signals to produce seismic data. Analysis of the seismic data can then indicate the presence or absence of probable locations of hydrocarbon deposits.

Some surveys are known as "marine" surveys because they are conducted in marine environments. However, "marine" surveys may not only be conducted in saltwater environments, but also in fresh and brackish waters. In one type of marine survey, called a "towed-array" survey, an array of seismic sensor-containing streamers and sources is towed behind a survey vessel. In one type of survey, called a "marine vertical seismic profile (marine VSP)" survey, an array of sensors is deployed in a borehole and the seismic source is either moving (e.g. towed behind a vessel) or stationary (e.g. suspended from a structure such has a drilling rig). In one type of marine survey, incorporating both hydrophones and geophones, called an "Ocean Bottom Cable (OBC)" survey, sensors are laid on the seabed. In another type of marine survey, the sensors are deployed in other ways and the seismic source is deployed in the water in some way, where the sensors or sources can be either moving or stationary. Other surveys are known as "land" surveys because they are conducted on land environments. Land surveys may use dynamite or seismic vibrators as sources. Arrays of seismic sensor-containing cables are laid on the ground to receive seismic signals. The seismic signals may be converted, digitized, stored or transmitted by sensors to data storage and/or processing facilities nearby, e.g. a recording truck. Land surveys may also use wireless receivers to avoid the limitations of cables. Seismic surveys may be conducted in areas between land and sea, which is referred to as the "transition zone".

Theoretically, in marine seismic surveys the sources can be impulsive sources (e.g. airguns) or continuous sources (e.g. marine seismic vibrators). However, marine seismic vibrators are not used in practice. It is desirable to be able to make marine seismic vibrators another practical type of source for marine seismic surveys.

SUMMARY

This summary is provided to introduce a selection of concepts that are further described below in the detailed description. This summary is not intended to identify key or essential features of the claimed subject matter, nor is it intended to be used as an aid in limiting the scope of the claimed subject matter.

This disclosure describes methods and apparatuses for marine seismic survey in which a marine seismic vibrator is used as the source. The methods include using vibrator sweep functions that reduce the need of desmearing data with vibrator sources, or increase the tolerance of distortion due to smearing, harmonics etc. The methods may also include using vibrator sweep functions that can provide adequate low frequency energy for seismic imaging. The apparatuses include marine seismic vibrators that can be used in marine seismic survey where the data can be desmeared easily or do not need desmearing at all.

In embodiments of the present invention, the marine seismic vibrators are used to generate seismic data, which is either inherently desmeared or can easily be desmeared, that may be processed to determine properties of a subterranean section of the Earth.

BRIEF DESCRIPTION OF DRAWINGS

Embodiments of this disclosure are described with reference to the following figures. The same numbers are used throughout the figures to reference like features and components. A better understanding of the methods or apparatuses can be had when the following detailed description of the several embodiments is considered in conjunction with the following drawings, in which:

FIG. 1 illustrates a seismic acquisition system in a marine environment;

FIG. 2 illustrates a monochromatic output power Em(f) of a marine vibrator;

FIG. 3 illustrates example signal-to-noise ratios (SNR) in a 2D seismic image using different sources;

FIG. 4 illustrates several sweep functions;

FIG. 5 illustrates several sweep functions and their SNR;

FIG. 6 illustrates a schematic view of a computer system where some methods disclosed can be implemented;

FIG. 7 illustrates a flow diagram for a method according to one embodiment;

FIG. 8 illustrates curves with constant phase errors in frequency domain or wavelength domain;

FIG. 9 illustrates errors of several sweep functions;

FIG. 10 illustrates errors of several sweep functions with distortions; and

FIG. 11 illustrates a flow diagram for a method according to one embodiment.

DETAILED DESCRIPTION

Reference will now be made in detail to embodiments, examples of which are illustrated in the accompanying drawings and figures. In the following detailed description, numerous specific details are set forth in order to provide a thorough understanding of the subject matter herein. However, it will be apparent to one of ordinary skill in the art that the subject matter may be practiced without these specific details. In other instances, well-known methods, procedures, components, and systems have not been described in detail so as not to unnecessarily obscure aspects of the embodiments.

It will also be understood that, although the terms first, second, etc. may be used herein to describe various elements, these elements should not be limited by these terms. These terms are only used to distinguish one element from another. For example, a first object or step could be termed

a second object or step, and, similarly, a second object or step could be termed a first object or step. The first object or step, and the second object or step, are both objects or steps, respectively, but they are not to be considered the same object or step.

The terminology used in the description of the disclosure herein is for the purpose of describing particular embodiments only and is not intended to be limiting of the subject matter. As used in this description and the appended claims, the singular forms "a", "an" and "the" are intended to include the plural forms as well, unless the context clearly indicates otherwise. It will also be understood that the term "and/or" as used herein refers to and encompasses any and all possible combinations of one or more of the associated listed items. It will be further understood that the terms "includes," "including," "comprises," and/or "comprising," when used in this specification, specify the presence of stated features, integers, steps, operations, elements, and/or components, but do not preclude the presence or addition of one or more other features, integers, steps, operations, elements, components, and/or groups thereof.

As used herein, the term "if" may be construed to mean "when" or "upon" or "in response to determining" or "in response to detecting," depending on the context. Similarly, the phrase "if it is determined" or "if [a stated condition or event] is detected" may be construed to mean "upon determining" or "in response to determining" or "upon detecting [the stated condition or event]" or "in response to detecting [the stated condition or event]," depending on the context.

Also, it is noted that the embodiments may be described as a process which is depicted as a flowchart, a flow diagram, a data flow diagram, a structure diagram, or a block diagram. Although a flowchart may describe the operations as a sequential process, many of the operations can be performed in parallel or concurrently. In addition, the order of the operations may be re-arranged. A process is terminated when its operations are completed, but could have additional steps not included in the figure. A process may correspond to a method, a function, a procedure, a subroutine, a subprogram, etc. When a process corresponds to a function, its termination corresponds to a return of the function to the calling function or the main function.

Moreover, as disclosed herein, the term "storage medium" may represent one or more devices for storing data, including read only memory (ROM), random access memory (RAM), magnetic RAM, core memory, magnetic disk storage mediums, optical storage mediums, flash memory devices and/or other machine readable mediums for storing information. The term "computer-readable medium" includes, but is not limited to portable or fixed storage devices, optical storage devices, wireless channels and various other mediums capable of storing, containing or carrying instruction(s) and/or data.

The current Applicant discloses methods and apparatuses to make using marine seismic vibrator practical, as disclosed in a co-pending application Ser. No. 14/003,769, filed on the same date, titled "METHODS AND SYSTEMS FOR MARINE VIBRATOR SWEEPS" by the same inventor. The disclosure in IS11.0203 is incorporated herein in its entirety by reference for all purposes.

FIG. 1 depicts a marine-based seismic data acquisition system 10. In system 10, a survey vessel 20 tows one or more seismic streamers 30 (one streamer 30 being depicted in FIG. 1) behind the vessel 20. It is noted that the streamers 30 may be arranged in a spread in which multiple streamers 30 are towed in approximately the same plane at the same

depth. As another non-limiting example, the streamers may be towed at multiple depths, such as in an over/under spread.

The seismic streamers 30 may be several thousand meters long and may contain various support cables (not shown), as well as wiring and/or circuitry (not shown) that may be used to support communication along the streamers 30. In general, each streamer 30 includes a primary cable into which are mounted seismic sensors 58 that record seismic signals. The streamers 30 contain seismic sensors 58, which may be hydrophones to acquire pressure data, geophones to acquired motion data, or multi-component sensors. For example, sensors 58 may be multi-component sensors, with each sensor capable of detecting a pressure wavefield and at least one component of a particle motion that is associated with acoustic signals that are proximate to the sensor. Examples of particle motions include one or more components of a particle displacement, one or more components (inline (x), crossline (y) and vertical (z) components (see axes 59, for example)) of a particle velocity and one or more components of a particle acceleration.

The multi-component seismic sensor may include one or more hydrophones, geophones, particle displacement sensors, particle velocity sensors, accelerometers, pressure gradient sensors, or combinations thereof.

The marine seismic data acquisition system 10 includes one or more seismic sources 40 (two seismic sources 40 being depicted in FIG. 1), such as air guns or other sources. The seismic sources 40 may be coupled to, or towed by, the survey vessel 20. The seismic sources 40 may operate independently of the survey vessel 20, in that the sources 40 may be coupled to other vessels or buoys, as just a few examples.

As the seismic streamers 30 are towed behind the survey vessel 20, acoustic signals 42 (an acoustic signal 42 being depicted in FIG. 1), often referred to as "shots," are produced by the seismic sources 40 and are directed down through a water column 44 into strata 62 and 68 beneath a water bottom surface 24. The acoustic signals 42 are then reflected from the various subterranean geological formations, such as a formation 65 that is depicted in FIG. 1.

The incident acoustic signals 42 that are generated by the sources 40 produce corresponding reflected acoustic signals, or pressure waves 60, which are sensed by the seismic sensors 58. It is noted that the pressure waves that are received and sensed by the seismic sensors 58 include "up going" pressure waves that propagate to the sensors 58 without reflection from the air-water boundary 31, as well as "down going" pressure waves that are produced by reflections of the pressure waves 60 from an air-water boundary 31.

The seismic sensors 58 generate signals (digital signals, for example), called "traces," which indicate the acquired measurements of the pressure wavefield and particle motion. It is noted that while the physical wavefield is continuous in space and time, traces are recorded at discrete points in space which may result in spatial aliasing. The traces are recorded and may be at least partially processed by a signal processor in unit 23 that is deployed on the survey vessel 20, in accordance with some embodiments. For example, a particular seismic sensor 58 may provide a trace, which corresponds to a measure of a pressure wavefield by its hydrophone; and the sensor 58 may provide (depending the sensor configurations) one or more traces that correspond to one or more components of particle motion.

One of the goals of the seismic acquisition is to build up an image of a survey area for purposes of identifying subterranean geological formations, such as the geological

formation **65**. Subsequent analysis of the representation may reveal probable locations of hydrocarbon deposits in subterranean geological formations. Depending on the particular survey design, portions of the analysis of the representation may be performed on the seismic survey vessel **20**, such as by the signal processor in unit **23**. In other surveys, the representation may be processed by a seismic data processing system (such as a seismic data processing system **600** in FIG. **6** and is further described below) that may be, for example, located in an office on land or on the vessel **20**.

A particular seismic source **40** may be formed from an array of seismic source elements (such as air guns or marine seismic vibrators, for example) that may be arranged in strings (gun strings, for example) of the array. A particular seismic source **40** may also be formed from one air gun, or a predetermined number of air guns, of an array, or may be formed from multiple arrays, etc. Regardless of the particular composition of the seismic sources, the sources may be fired in a particular time sequence during the survey.

Theoretically, either impulsive sources or continuous sources can be used in seismic surveys. In practice, both impulsive sources and continuous sources are used in seismic surveys performed on land. However, continuous sources (e.g. marine seismic vibrators) are almost never used in commercial marine seismic surveys. There are many characteristics of marine seismic vibrators that prevent them from being used as practical sources. One of the characteristics is its low acoustic power, especially at low frequencies, compared to airguns. Low power at low frequencies may degrade the resulting seismic images to an unacceptable level. This same characteristic—low power—means there is low environmental impact during surveys, which is desirable because of environmental protection, especially for the protection of marine fauna, which is of concern during seismic exploration. Compared to the impulsive sources (e.g. airguns) which can emit an impulse that covers the entire spectra all at once, a vibrator can vibrate at each individual frequency in the spectra in sequence to provide source energy to cover the entire spectra. The amount of time for a vibrator to sweep the entire spectrum is limited due to production or operational requirements. This may also limit the total energy over the entire spectrum.

Another aspect that limits marine seismic vibrators' usage in marine seismic surveys is the complexity of using a marine seismic vibrator to replicate the output energy spectrum of a common airgun array. Previously, the use of marine seismic vibrators has not been desirable, practicable and/or the like because it may take complex arrangements, such as the system and method disclosed in U.S. Pat. No. 6,942,059, titled "Composite Bandwidth Marine Vibroseis Array" assigned to the current assignee, to configure a marine seismic vibrator to produce an output/sweep that is equivalent to that of an airgun or airgun array.

FIG. **2** illustrates an example of monochromatic output power spectra Em(D of a marine seismic vibrator for illustrative purposes. The output power is substantially constant above a certain roll-off frequency. In this example it is about 10 Hz. Below this roll-off frequency, the output power rolls-off and eventually becomes insufficient for a seismic survey. The roll-off may be caused by the finite swept volume of the vibrator and may be proportional to the frequency squared. For seismic surveys, frequency content (e.g. several Hz) below this roll-off frequency (e.g. 10 Hz) may still be needed. The plateau above the roll-off frequency may be caused by limitations in the mechanism that drives the vibrator. The output power spectra from a marine seismic vibrator as shown here is very different from the power

spectra of a common airgun, one of which is illustrated in FIG. **5**, curve **535**, which will be discussed later. It is difficult to use a marine seismic vibrator to achieve the power spectra of an airgun.

FIG. **3** illustrates some SNRs in a seismic image where the data were acquired using an airgun array. It illustrates the relationships between seismic image quality and various parameters in acquiring the seismic data. The data were derived from a conventional 2D seismic line that was acquired in the Gulf of Mexico using an airgun array. The same line was also acquired without firing the airguns (stealth section with noise only) so that the noise image could be created using the same processing. The image data were sliced into 1 second windows, depending on the target depth, in terms of TWT, (TWT=two way time, travel time from source to target to receiver). The 1 second window image data are transformed into frequency domain, and then divided by the noise spectra to derive SNR as shown in FIG. **3**. Each curve (**302-307**) shows the SNR for the image in the 1 second window, e.g. curve **302** is for a window of TWT 2-3 seconds, curve **303** is for TWT 3-4 seconds, curve **304** is for TWT 4-5 seconds, **305** is for TWT 5-6 seconds, **306** is for TWT 6-7 seconds, and **307** is for TWT 7-8 seconds. An image that has a minimum SNR of about 20 dB might often be considered of good quality. While an SNR below 20 dB at some spectra may degrade a seismic image, sometimes to an unacceptable level, an SNR greatly above 20 dB at other parts of the data do not confer any benefit for the resulting seismic image as a whole. For example, for TWT at 4-5 seconds (**304**) at 40 Hz, the output is about 32 dB above noise, which is 12 dB higher than it needs to be to give a 20 dB image. For shallow targets (e.g. for TWT less than 4 seconds), the 20 dB SNR range is fairly large (about 12 Hz and above in this example). At targets with TWT=4-5 seconds (**304**), for example, an SNR of 20 dB is achieved between about 15 Hz and 70 Hz, slightly narrower. At deeper targets (**305**, **306** or **307**), the SNR is insufficient for the 20 dB quality level. While for shallow targets, the SNRs are greatly above the needed quality, for deeper targets (TWT greater than 6 s), the SNR may be insufficient.

From FIG. **3**, where the source is an airgun, it can be seen that the energy density distribution is uneven. At the high frequency end, there is more energy from the airgun than necessary for a set image quality, i.e. at a desired SNR requirement. The energy spectrum of an airgun is not optimal for seismic imaging purpose. To obtain a seismic image at a set image quality, it is not necessary to match the energy density spectra to that of airguns. In other words, when marine vibrators are used, they do not need to match the spectra of airguns. Marine vibrators may be used to provide certain spectral energy density based on resulting seismic image quality, rather than the spectral content of an airgun. Such image quality based spectral energy distribution, or sweep functions may be more beneficial and efficient.

In this disclosure, the marine seismic vibrator(s) may be controlled/driven to produce a seismic sweep/sweep function that is configured to provide and/or is based on a quality requirement, rather than on a requirement to match the output energy of a typical airgun array or to produce a standard flat-spectrum. In accordance with methods or apparatuses disclosed below, by configuring the marine seismic vibrators for a sweep function based on image quality requirement or other quality requirement, the marine vibrator may be able to provide sufficient energy for a seismic survey. In aspects of the methods discussed below, a sweep function for a marine seismic vibrator may be designed

based upon an image quality requirement and/or an environmental impact quality requirement. In this way, a marine seismic vibrator may be configured to produce a seismic sweep that is more environmentally friendly than is produced by an airgun source. In addition, a sweep may be changed during the seismic survey as the noise and/or environmental impact conditions change.

For ease of discussion, the quality of image as defined by SNR is set at an arbitrary level, e.g. 18 dB for the remaining discussion. This SNR quality level may be set at a higher (e.g. 20 dB as used earlier) or lower level, depending on the needs or uses of the resulting image. The sweep functions can be determined that give that SNR over as wide a frequency range as possible. The SNR might be chosen to be a function of frequency.

FIG. 4 illustrates three sweep functions for marine vibrators and FIG. 5 illustrates their corresponding energy curves in terms of SNR. In FIG. 4, the horizontal axis is time (seconds) in linear scale while the vertical axis is frequency (Hz) in logarithmic scale. The blue curve 410 illustrates a linear sweep (meaning that the frequency is a linear function of time), which is a common sweep scheme for vibrators; the red curve 420 is a sweep that matches the spectra content of an airgun; and the orange curve 430 is a sweep that is based on an 18 dB image SNR requirement. The orange sweep 430 matches a specified image SNR requirement at a desired/defined target depth and/or minimizes the emission of superfluous acoustic energy. Using the orange sweep 430, vibrators may produce the best image quality among the three sweeps 410, 420 and 430. Moreover, synergistically, the orange sweep 430 is more environmentally friendly than the other two sweeps.

FIG. 5 illustrates equivalent source energy levels in dB for sweeps illustrated in FIG. 4 and a background noise energy level. The horizontal axis is frequency in Hz in logarithmic scale; the vertical axis is source energy level in dB. The black dotted curve 502 is the background noise energy spectra, equivalent to that measured in the examples as shown in FIG. 3. A noise source with this level, when passed through the processing, gives an image noise the same as that in FIG. 3. To achieve a constant 18 dB image quality, a source may have an energy curve as the orange dotted curve 532, which is 18 dB above the background noise 502. The solid blue curve 510 is the linear sweep; the solid red curve 520 is the sweep that tries to match the energy spectra of an airgun, which is the dotted red curve 535 that extends on both sides of the solid red curve 520. Because the sweep time is limited, in this example, 5 seconds, a marine seismic vibrator may not cover the entire spectrum 535 of an airgun. In some operations, the sweeping time may be extended to 10, 15 seconds or longer, to obtain data from deeper targets. In those cases, the frequency band may also be extended, on either the low frequency end or high frequency end, or both. The solid orange curve 530 is the sweep that follows the 18 dB SNR curve. FIG. 5 illustrates the energy spectral density for targets at 4-5 sec TWT.

Knowing the background noise level as shown in the black dotted line 502, a sweep that has constant SNR is simply the orange dashed curve 532, which is the background noise sweep plus the desired SNR, i.e. 18 dB. The background noise 502, as illustrated in this example, has a large barrier above about 80 Hz resulting from the source depth that was used in the test that generated the data in FIG. 3 and rises steadily below about 20 Hz as frequency decreases. The source noise level 502 is that which, if emitted by a source and then processed to an image in the same as the signal is, would yield an image noise level that

matches the level found in the image of the test that generated the curves in FIG. 3. Curve 502 is the image noise expressed as an equivalent source level.

In a linear sweep 510 (blue line), the energy is spread out between a large range from about 5 Hz to about 83 Hz. However, the range with 18 dB SNR is about 19-80 Hz. At the low frequency end, the source energy holds flat till about 10 Hz and then decreases, while noise energy goes up steadily; the SNR degrades quickly at low frequencies. If a survey uses this type of a sweep, the useable frequency range is about 19-80 Hz. The sweep line 517 near the bottom of FIG. 5 illustrates that the sweep covers the entire frequency range 5 Hz to 83 Hz with equal amounts of time.

In a sweep 520 that simulates the airgun spectra (red line), the source energy does not fall as frequency decreases at the low frequency end. In order to cover the spectrum while still within the 5 second sweep time, the range of frequency swept is less than the linear sweep 510. In this case, the sweep range is from about 12 Hz to about 70 Hz (see the bottom red line 527). For nearly the entire sweep, the SNR is above the quality requirement, the 18 dB. The useable frequency range at low frequency end extends to 12 Hz, compared to the 19 Hz for a linear sweep 517. If an actual airgun is used, the spectra would be extended to the dotted red line 535, which ends at about 5 Hz. The spectrum range would be larger, but the useable spectra range (i.e. SNR above 18 dB) would be substantially the same in this example.

In a sweep 530 that follows a constant SNR (orange line 530), the frequency coverage is the largest, from about 9.5 Hz to 70 Hz. In this case, the majority of the sweep time is spent in sweeping the low frequency end, where the energy need is the greatest and when the vibrator monochromatic power is often the most limited. For example, the vibrator spends 1 second just to cover the lowest frequency band from about 9.5 Hz to 10 Hz, and 4 seconds for frequencies below about 16 Hz, while a large high frequency band, from 16-70 Hz is covered in 1 second. In this sweep 530, the useable frequency range is about 9.5 Hz to 70 Hz. The low end frequency extended to below 10 Hz, compared to airgun sweep 520 to 12 Hz, linear sweep 510 to 19 Hz.

Sweep 530 is highly non-linear. In this example, the vibrator spends 4.2 seconds (about 85% of the 5 seconds sweep time) sweeping through low frequency band 9.5-18 Hz (8.5 Hz, or about 15% of the 61.5 Hz bandwidth); while spending 0.8 seconds (about 15% of sweep time) sweeping through the remaining high frequency band 18-70 Hz (52 Hz, or about 85% of the 61.5 Hz bandwidth).

Sweep 530 is very different from the behavior of the marine seismic vibrator when it is used to produce a conventional linear sweep 510 or a sweep 520 that is designed to match one produced by an airgun array (red). These last two sweeps 510 and 520 by the marine seismic vibrator emit too much energy at mid to higher frequencies, for example, above about 17 Hz. Sweeps 510 and 520 emit too little energy at lower frequencies, for example, below about 17 Hz. They do not produce the necessary/desired SNR across the sweep frequencies.

In the examples illustrated in FIGS. 4 and 5, the sweep time is limited to 5 seconds. If sweep time were extended, then more energy would be available and more frequency range would be covered.

One method 700 may be summarized in a flow diagram as shown in FIG. 7. The method 700 using marine seismic vibrator may proceed as follows:

Obtaining a quality requirement, e.g. SNR over an image background noise over the image bandwidth (710);

Setting a sweep function that based on the quality requirement, e.g. the energy curve that is 18 dB above the background noise (**720**);

Controlling the vibrator according to the sweep function (**730**) and collecting data.

The quality requirement can be an image quality requirement of a final image, such as a set SNR. The image quality requirement can be a set of functions of frequencies, not necessarily related to SNR. The quality requirement can be an environmental quality requirement, such as an energy limitation at certain frequency range for marine mammal protection or a limit on superfluous emitted energy. When SNR is used, the image background noise may be obtained from direct measurement of the noise and an approximation to the processing method, as in the above example or from past experience in a similar survey area, similar weather or survey equipment. The direct measurement may be done prior to a survey, as in the above example. The direct measurement of noise may also be done during a survey in real-time, i.e. let sensors record signals while the sources are not activated. The sweep function may be determined based on the real-time noise.

The background noise may also be estimated from general knowledge of the survey design. The quality requirement may be a compromise between several goals, for example, the sweep design factor may include the geophysical goals of: (1) required image SNR; (2) low and high frequency limits of the image bandwidth; (3) environmental goals, including but not limited to minimizing environmental impact assessed, for example, by minimizing superfluous emitted acoustic energy.

In one embodiment, the design of the sweep for the marine seismic vibrator/marine seismic vibrator array may take place before the survey is conducted, using assumed values for the noise spectra, the earth seismic response, the SNR, the processing sequence and/or the environmental requirements. In other embodiments, the design of the sweep for the marine seismic vibrator/marine seismic vibrator array may be calculated/determined/processed during the survey using noise records, SNR, sweep characteristics and/or the like acquired, for example, at the start and/or end of each seismic sweep. This may be used to revise the sweep during the survey in the light of the particular noise conditions that are encountered at the time. The sweep may also be modified to take account of locally varying environmental requirements such as the actual positions of marine mammals in the area at the time of the seismic survey.

In operation, more than one marine seismic vibrator may be deployed, as multiple sources **40** illustrated in FIG. **1**. The vibrators may be deployed at various depth (e.g. over/under configurations), or in-line or cross-line locations for desired wavefield formation.

For simplicity, FIG. **1** only illustrates a towed marine seismic survey, which is one of the many marine seismic surveys. In a towed marine seismic survey, both sensors and sources are towed by one or more vessels and travel along with the towing vessels during the survey. There can be many other types of marine seismic surveys, as mentioned before. In some of these surveys, the sensors can either be stationary or moving during a survey. The sources (e.g. marine seismic vibrator) can also be either stationary or moving during a survey.

Part of the methods discussed above may be easier to understand using math formulas. A sweep for a marine seismic vibrator may be designed based on required properties of the resulting seismic image. The down-going source

energy spectrum of a marine seismic vibrator array, excluding effects of the sea surface reflection, is given approximately by:

$$S(f) = N^2 * Em(f) * (dt/df)$$

where: Em(f) is the power emitted by a single vibrator if it is driven continuously at a single frequency f Em(f) is a characteristic of a vibrator, which may vary from vibrator to vibrator. An example is illustrated in FIG. **2**. N is the number of vibrator units.

If the source energy spectrum S(f) is defined then dt/df can be determined and thence f(t), which is the sweep function. For a linear sweep, df/dt is a constant. When a vibrator is used to simulate an airgun, S(f) is the energy spectrum of an airgun, as curve **535** shown in FIG. **5**. The sweep function to generate the energy spectrum is also shown in FIGS. **4** and **5**.

In operation, the available duration of the sweep and the number of marine seismic vibrator units in the vibrator array limits the range of frequencies over which the spectrum sweep produced by the marine seismic vibrators can be made to match a given source energy spectrum requirement, e.g. $f(t_{max})=f_{max}$, then $f(0)=f_{min}$. For example, in order to match a desired sweep, such as that produced by an airgun array, the marine seismic vibrator may be driven to produce a spectra match at some upper frequency of the desired sweep. Then the sweep may be designed downwards from this upper frequency until the sweep duration limit is reached. The sweep duration would then impose a low frequency limit on the spectrum of the sweep; below this limit it would not meet the requirement. This is illustrated in FIG. **5** (red curve **520**). When the maximum frequency 70 Hz and sweep time of 5 seconds are set, the minimum frequency a sweep can reach is limited to about 16 Hz. To increase the frequency range (e.g. decrease the minimum frequency limit), one may increase the sweep time, although the increase of sweep time may decrease the survey productivity.

In some embodiments, more than one vibrator array may be used in a seismic survey. In such cases, the sweep design methods may be applied to each marine seismic vibrator array. Marine seismic vibrators may be deployed at a range of depths and the methods discussed here can be applied to any depth.

In some embodiments, a new marine vibrator array may be manufactured or adapted from existing vibrators. The marine vibrator array can be used as a source for marine seismic surveys. The marine vibrator array has at least one marine seismic vibrator. A vibrator controller is associated with the vibrator array, where the vibrator controller can control the operation of the vibrator to sweep through frequency ranges according to one or more sweeping functions. The sweep function can be based on a quality requirement. The sweep function can be a function of frequency. The quality requirement may be any one of the quality requirements mentioned above. The vibrator controller can be a dedicated controller or as part of a control system for the survey. The vibrator array may be towed by a dedicated source vessel or by a seismic vessel which tows marine streamers for the survey.

In the above discussion, the examples are based on 2D surveying data. However, for 3D seismic surveys, the advantage of the methods or apparatuses discussed above might be greater because the stack-fold is larger. The above discussed methods or apparatuses may be equally applied.

The methods and apparatuses, as disclosed in the co-pending application, filed as PCT/IB2012/051153 on 2012

Mar. 12 and titled MARINE VIBRATOR SWEEPS, make using marine seismic vibrators practical. However, there are still a few issues associated with marine survey using continuous sources. Unlike continuous sources (e.g. vibrators) used in land seismic surveys, where the sources are stationary during vibration, in some marine seismic surveys, the sources move significant distances during vibration, i.e. while source signals are being emitted. In a common marine survey, a seismic vessel tows sources and receivers at a speed of about 2.5 m/s. During the course of a 5-second sweep, the vessel (and all sources and receivers) moves 12.5 m; during a 10-second sweep, it moves 25 m. These distances are not negligible where the resolution of seismic images is in the order of meters.

To visualize the smear process, consider a linear upsweep from 5 Hz to 75 Hz spread over 10 seconds. The 75 Hz component and the 5 Hz component of the final image will have been made with the sources all effectively displaced by 25 m. One may imagine a family of separate monochromatic images that are all differently displaced by the smearing. The 75 Hz image will be displaced by 25 m relative to the 5 Hz image for example. A correction (e.g. desmearing) may be necessary. To desmear is to shift the images by the appropriate distance and adding them, although it may not be implemented necessarily this way.

The correction (desmearing) may be, in principle, straightforward but it may be complicated by two things: (1) the data are under-sampled in common receiver domain where the desmearing is usually performed, and (2) there are distortions (harmonics) in the vibrator output. One advantage of the marine case (over land) is that the source signature, including the harmonics, may be accurately measured, e.g. via near field hydrophones.

A phase error caused by smearing with a sinusoidal vibrator may be the phase shift caused by the distance between the nominal shot position x_0, and the position $x(f)$ when the vibrator emits the frequency in question. The phase error may be expressed as:

$$E(f, TOA) = \left\{ \frac{dt}{df}(f) \right\}^{\frac{1}{2}} \cdot B(f) \cdot \exp\{i[x(f) - x_0] \cdot \sin(2\pi f \cdot TOA)\} \qquad \text{Eq. 1}$$

where:
E(f,TOA) is the phase error at frequency f and take-off angle TOA,
B(f) is the monochromatic amplitude of the vibrator of frequency f,
x(f) is the position at which frequency f is emitted,
x_0 is the nominal shot position,

$$\frac{dt}{df}(f)$$

is the reciprocal of the sweep rate at frequency f,
TOA is the take-off angle (to the vertical) of the far field direction.

Once a sweep function is f(t) selected, the phase error may be evaluated over the range of TOA for each sweeping frequency. The largest error over the TOA range may be used as the error of the frequency. FIG. 8 illustrates phase error contours for several different sweep functions.

Error criteria may be set as the maximum amplitude and phase errors. For the examples discussed below, the error

thresholds are set in the deconvolved and desmeared (if appropriate) far-field signatures at an emission take-off angle (TOA) between 0 (vertical) to about 22 degrees. This range of TOA is chosen as being typical of the signal that enters the subsurface and is chosen for illustrative purpose. These error criteria may be that: the source signatures have a far-field error of less than 3.4 degrees in phase and 0.5 dB in energy over the range of TOA. These criteria leave an error of about 6% of the amplitude of the signal, i.e. 24 dB down at the shot level. These arbitrary error thresholds are chosen for ease of discussion. The actual error thresholds may be selected based on many survey design or quality parameters.

In the examples discussed below, the sweep lengths are 5 or 10 seconds and the depth of deployment is 8 m. These are illustrative examples, and any other sweep length or deployment depth may be used.

Several sweeps are compared in the discussion below, including a common "linear-frequency" sweep (blue curve, e.g. 830 in FIG. 8), meaning the fundamental sweep frequency is a linear function of time; a "linear-wavelength" sweep (red curve, e.g. 806, 812, 816 and 822), meaning the fundamental wavelength is a linear function of time; a "negligible error" sweep (e.g. 803 or 804), meaning the phase error is below the error threshold (i.e. negligible) and desmearing may be omitted; and an "SNR-based" sweep (e.g. 840), meaning the sweep function is given based on a defined image signal-to-noise-ratio (SNR) or other quality based criteria, as discussed in the co-pending application, filed as PCT/IB2012/051153 on 2012 Mar. 12, and titled MARINE VIBRATOR SWEEPS, which is incorporated herein for all purposes.

FIG. 8 illustrates phase errors for several different sweeps with 5-second sweep length. The top chart shows the phase errors as functions of frequency and sweep time for a sinusoidal vibrator; the bottom chart shows the phase errors as functions of wavelength and sweep time for the similar sinusoidal vibrators. In these examples, it is assumed that the vibrators emit only fundamental frequencies, i.e. sources emit only one frequency at a time according to the sweep function, and each frequency is emitted at one position only. The dashed curves 820, 815, 810, 805 and 803 are constant-phase-error curves with phase errors range from 20 degrees, 15, 10, 5 and 3.4 degrees respectively. For example, the curve 820 illustrates a curve with constant 20-degree phase error during a sweep. The curve 803 illustrates a curve that has a constant phase error of 3.4-degrees. This curve 802 can be a sweep function, and if a vibrator sweeps through frequencies according to this curve, the resulting phase error in the resulting image is 3.4 degrees, which may be negligible for many purposes.

The same upper chart in FIG. 8 also illustrates two other sweep curves, one blue curve 830, a linear frequency sweep, and an orange curve 840, an SNR based sweep. As illustrated in this chart, if a linear frequency sweep 830 is used, then the phase errors are substantial at most frequencies. For example, for frequencies between about 50 Hz-25 Hz, the phase errors are greater than 20 degrees. For a few frequencies at the very top (above 70 Hz) or very bottom (below about 5 Hz), the phase errors are below or close to the negligible level (i.e. 3.4 degrees).

From this chart, it can be seen that even though the sweep 840 is an image-quality-based sweep, its phase errors at most frequencies are fairly small. In this example, for high frequencies above approximately 15 Hz, the phase errors can be negligible (i.e. below 3.4 degrees error threshold). For frequencies between 15 Hz to 12 Hz, the phase errors are

between 4-10 degrees. It is only for frequencies below approximately 12 Hz that the phase errors are significant, i.e. above 10 degrees. If sweep **840** is used as the sweep function, then desmearing may be necessary for frequencies below approximately 15 Hz or for sweep time after 1 second. At the lower frequency end (e.g. below approximately 15 Hz), data under-sampling or aliasing may not be a problem. Therefore, desmearing can be done much more easily with this sweep than in a case where high frequencies and aliasing problems are encountered.

The bottom chart of FIG. **8** illustrates similar phase errors, but in a wavelength domain. In this bottom chart of FIG. **8**, the constant phase error curves **804**, **806**, **812**, **816** and **822** are curves with constant phase errors of 3.4, 5, 10, 15 and 20 degrees, respectively. The blue curve **832** is a linear-frequency sweep curve and the orange curve **842** is an SNR-based sweep. The green curve **804** is a sweep that has a 3.4 degrees phase error, which may be a negligible error for many purposes and desmearing may be omitted.

The green curve **804**, or "negligible smear" sweep follows roughly the form of f(t)=15/t, where f is the frequency in Hz, t is the time in seconds and the phase error threshold is set at 3.4 degree; or more generally f(t)=4.4φ/t, where φ is the acceptable phase error in degrees.

When marine seismic vibrators do not emit distortions, as in examples in FIG. **8**, the desmearing process may be done as discussed above. In some cases, by selecting some sweep functions, desmearing may be unnecessary.

FIG. **9** illustrates comparisons of sweeps as discussed in FIG. **8** and as when desmearing processes are applied. In these examples, it is assumed that the sources do not emit distortions, i.e. harmonic frequencies. The dashed curves **930**, **940** and **903** illustrate the errors (phase errors in top chart, amplitude errors in bottom chart) for a linear-frequency sweep, an SNR-based sweep, and a negligible-smear sweep. Once desmearing processes are applied, all phase errors may be corrected as shown in the solid curves **932**, **904**, **942** in FIG. **9**. The amplitude errors **950** are negligible even without desmearing correction in these examples where there is no distortion, while the amplitude error threshold **955** is set at 0.5 dB. Sinusoidal desmearing may completely correct the errors for a sinusoidal vibrator.

For many vibrators, in addition to sinusoidal output, they may also emit harmonics. Unlike vibrators in land seismic surveys, the actual source signals may be monitored by accelerometers mounted on the vibrators.

Because of the harmonic distortions where sources may emit each frequency at several different positions, the desmearing process is more complicated than where there is no harmonic distortion. For example, a source may emit 60 Hz at the position when a sweep is demanding 60 Hz, but it may also emit 60 Hz as a harmonic when the sweep is demanding 30 Hz, 20 Hz or 15 Hz and so on. If sinusoidal desmearing is used, then the assumption is made that all the 60 Hz energy has been emitted at position X1 when a sweep is demanding 60 Hz. This leads to an error for the nth harmonics for non-vertical emission because that energy was emitted at X2 (30 Hz), X3 (30 Hz), X4 (15 Hz) etc. The signal error due to the position of the harmonics may be expressed as in Eq. 2. If the desmearing is omitted then the remaining error may be expressed in Eq. 3. Eq. 3 becomes Eq. 1 if all the A(i) are set to zero for i>1, i.e. for a sinusoidal source.

$$E(f, TOA) = \sum_{n=1}^{\infty} \left\{ \frac{\frac{dt}{df}\left(\frac{f}{n}\right)}{n} \right\}^{\frac{1}{2}} \cdot B\left(\frac{f}{n}\right) \cdot A(n) \cdot \exp \qquad \text{Eq. 2}$$

-continued

$$\left\{ i\left[x\left(\frac{f}{n}\right) - x(f) \right] \cdot \sin(2\pi f \cdot TOA) \right\}$$

where:

B(f) is the fundamental nomochromatic amplitude of the vibrator of frequency f,

n is the harmonic number,

A(n) is the complex amplitude of the nth harmonic of the waveform, A(1)=1,

x(f) is the position at which frequency f is emitted,

$$\frac{dt}{df}(f)$$

is the reciprocal of the sweep rate at frequency f. This quantity, divided by the harmonic number, is therefore the dt/df for that harmonic.

$$E(f, TOA) = \sum_{n=1}^{\infty} \left\{ \frac{\frac{dt}{df}\left(\frac{f}{n}\right)}{n} \right\}^{\frac{1}{2}} \cdot B\left(\frac{f}{n}\right) \cdot A(n) \cdot \exp \qquad \text{Eq. 3}$$

$$\left\{ i\left[x\left(\frac{f}{n}\right) - x_0 \right] \cdot \sin(2\pi f \cdot TOA) \right\}$$

where: x_0 is the nominal shot position. All other symbols are the same as in Eq. 2.

FIG. **10** illustrates comparisons of sweeps as discussed in FIG. **8** and as when desmearing processes are applied in FIG. **9**. Unlike the examples as shown in FIG. **9**, in these examples in FIG. **10**, it is assumed that the sources do emit distortions, i.e. harmonic frequencies. The amounts of distortion, which are the ratios of the energies of all harmonic frequencies over the energy of the fundamental frequency, in these examples are about 7.9%. With harmonic distortions, the phase errors and amplitudes errors for the linear-frequency sweep (blue curve **1030**, **1032**) and SNR-based sweep (orange curve **1040**, **1042**) are non-negligible, so desmearing is necessary. Even after desmearing, the phase errors are not completely corrected (**1033**, **1043**). For a linear sweep, the phase error curve **1033** grows from a near zero degree at about 20 Hz to 8 degrees at 75 Hz. For an SNR-based sweep **1043**, even after desmearing the phase error is about 4 degrees between about 28 Hz to approximately 50 Hz and becomes infinite at 70 Hz. For the "negligible smear" sweep **1003** and **1004**, the errors are also larger than the last examples. In these "negligible smear" sweeps, the phase errors for both phase and amplitude are still small enough to remain negligible. The amplitude error for linear sweep **1034** is non-negligible above approximately 40 Hz, even after desmearing, or the desmearing process cannot properly correct the errors due to the harmonic distortion. For SNR-based sweep or "negligible smear" sweep, amplitude errors **1044** and **1006** are still negligible.

It can be seen that a linear frequency sweep is not an optimum sweep function for a marine seismic vibrator. When smearing and harmonic distortion is of concern, the data acquired by linear frequency sweep may contain large errors even after the desmearing process. The SNR-based sweep may provide data with fewer errors, and much of the errors may be corrected by desmearing process. The "neg-

15

ligible smear" sweep may provide data that contains negligible smear errors and may not require the desmearing process during data process.

When a continuous source, such as a marine seismic vibrator or a land seismic vibrator, is used, deconvolution is frequently used to compress the acquired data in time domain. Before a deconvolution process is performed on the acquired seismic data, desmearing may be necessary. As shown above, when a "negligible smear" sweep is used, the errors are sufficiently small such that the desmearing process is not necessary. If other sweeps are used, errors may not be negligible and desmearing may be necessary. In many operations, harmonic distortion is common, as shown in FIG. **10**, which is when harmonic frequencies, in addition to the sweeping fundamental frequencies, are also emitted by vibrators. Desmearing is performed using knowledge of what frequencies were emitted at what positions. Desmearing compresses the source in space.

Source-signature deconvolution is performed using an estimate of the source signature. Theoretically it is possible to desmear and deconvolve in one step and convert the data to what would have been received using an impulsive source at the nominal shot locations. However, it may be more convenient if it is done in two simplified steps: 1) "deconvolution ignoring smear" followed by 2) "sinusoidal desmear".

It is noticed that the higher frequencies need to be more accurately positioned than the lower frequencies. As shown in the examples, it is better to sweep downwards in frequency. In land surveys, vibrators usually sweep upwards; this is so that the errors in source signature estimation appear earlier in the trace (where the signal is stronger).

In FIG. **11**, a method **1100** may be summarized as follows:
Selecting smearing error criteria (**1110**);
Selecting a downward-sweeping nonlinear sweep function (**1120**);
Computing smearing errors for each frequency (**1130**);
Activating vibrators according to the sweep function (**1140**);
Acquiring marine seismic data (**1150**); and
Performing desmearing on the acquired data for frequencies where the smearing errors are above the criteria (**1160**).

Once the smearing errors are corrected, the data may be processed further for other purposes, such as processing the data further for seismic imaging, seismic modeling, seismic interpretation, etc.

It is noted that not all actions in method **1100** are needed. For example, if a sweep function is selected according to the smearing error criteria, e.g. the "negligible smear" sweep, then the resulting data will have smearing errors at or below the error criteria. Smearing errors do not need to be computed and no desmearing is necessary. The actions **1130**, **1160** are not needed.

If the selected sweep function curve is below the smearing error curve, which is roughly 15/t in some of the above examples, e.g. selecting an f(t)<15/t, then the resulting smearing errors are also below the error criteria. In that case, desmearing is not necessary either.

For marine seismic data acquisition operation, the data processing activities may not need to be performed. The data acquired may be processed later on in a separate data processing operation. In that case, the computing smearing errors (**1130**) and desmearing operation (**1160**) need not be performed during data acquisition operation. During data processing operation, with known sweep functions and the corresponding acquired data, smearing errors may be com-

16

puted and compared with smearing criteria. If necessary, the desmearing operation may be performed during the data processing.

When SNR based sweep function is used, smearing errors only occur at low frequencies (e.g. below 15 Hz), so desmearing is only needed at low frequencies.

The smearing error criteria and sweep functions are selected prior or during a marine seismic survey. When proper sweep functions are selected, then smearing problems may be avoided, and the desmearing process is not necessary. In that case, during data processing, the acquired data may be processed as if there were no smearing problem.

As those with skill in the art will understand, one or more of the steps of methods discussed above may be combined and/or the order of some operations may be changed. Furthermore, some operations in methods may be combined with aspects of other example embodiments disclosed herein, and/or the order of some operations may be changed. The process of measurement, its interpretation, and actions taken by operators may be done in an iterative fashion; this concept is applicable to the methods discussed herein. Finally, portions of methods may be performed by any suitable techniques, including on an automated or semi-automated basis on computing system **600** in FIG. **6**.

Portions of methods described above may be implemented in a computer system **600**, one of which is shown in FIG. **6**. The system computer **630** may be in communication with disk storage devices **629**, **631**, **633** and **635**, which may be external hard disk storage devices and measurement sensors (not shown). It is contemplated that disk storage devices **629**, **631**, **633** and **635** are conventional hard disk drives, and as such, may be implemented by way of a local area network or by remote access. While disk storage devices are illustrated as separate devices, a single disk storage device may be used to store any and all of the program instructions, measurement data, and results as desired.

In one implementation, real-time data from the sensors may be stored in disk storage device **631**. Various non-real-time data from different sources may be stored in disk storage device **633**. The system computer **630** may retrieve the appropriate data from the disk storage devices **631** or **633** to process data according to program instructions that correspond to implementations of various techniques described herein. The program instructions may be written in a computer programming language, such as C++, Java and the like. The program instructions may be stored in a computer-readable medium, such as program disk storage device **635**. Such computer-readable media may include computer storage media.

In one implementation, the system computer **630** may present output primarily onto graphics display **627**, or via printer **628** (not shown). The system computer **630** may store the results of the methods described above on disk storage **629**, for later use and further analysis. The keyboard **626** and the pointing device (e.g., a mouse, trackball, or the like) **625** may be provided with the system computer **630** to enable interactive operation.

The system computer **630** may be located on-site, e.g. as a part of unit **23** on-board a vessel **20** as in FIG. **1**. The system computer **630** may be in communication with equipment on site to receive data of various measurements. Such data, after conventional formatting and other initial processing, may be stored by the system computer **630** as digital data in the disk storage **631** or **633** for subsequent retrieval and processing in the manner described above. While FIG. **6** illustrates the disk storage, e.g. **631** as directly connected

to the system computer **630**, it is also contemplated that the disk storage device may be accessible through a local area network or by remote access. Furthermore, while disk storage devices **629**, **631** are illustrated as separate devices for storing input data and analysis results, the disk storage devices **629**, **631** may be implemented within a single disk drive (either together with or separately from program disk storage device **633**), or in any other conventional manner as will be fully understood by one of skill in the art having reference to this specification.

Although only a few example embodiments have been described in detail above, those skilled in the art will readily appreciate that many modifications are possible in the example embodiments without materially departing from this invention. Accordingly, all such modifications are intended to be included within the scope of this disclosure as defined in the following claims. In the claims, means-plus-function clauses are intended to cover the structures described herein as performing the recited function and not only structural equivalents, but also equivalent structures. Thus, although a nail and a screw may not be structural equivalents in that a nail employs a cylindrical surface to secure wooden parts together, whereas a screw employs a helical surface, in the environment of fastening wooden parts, a nail and a screw may be equivalent structures.

What is claimed is:

1. A method for operating a marine seismic vibrator as a moving source in a marine seismic survey, the method comprising:

selecting smearing error criteria;

selecting a downward-sweeping nonlinear sweep function, based on a smearing error criteria;

activating the marine seismic vibrator according to the sweep function; and

acquiring marine seismic data.

2. The method of claim **1**, further comprising:

processing the acquired marine seismic data to determine properties of an interior section of the Earth.

3. The method of claim **1**, wherein the smearing error criteria comprises a phase error threshold and an amplitude error threshold.

4. The method of claim **3**, wherein the downward-sweeping nonlinear sweep function f(t), as expressed in a frequency-time domain is a function that is equal or less than the smearing error criteria.

5. The method of claim **4**, wherein the phase error threshold is φ in degrees and the sweep function is a function that is equal to or less than 4.4φ/t.

6. The method of claim **1**, further comprising:

computing smearing errors for each frequency; and

performing desmearing on acquired data for frequencies in which smearing errors are above the smearing error criteria.

7. The method of claim **6**, wherein performing desmearing on the acquired data includes performing desmearing on a low frequency end of the acquired data up to 20 Hz.

8. The method of claim **1**, wherein the sweep function comprises a function based on a quality requirement.

9. The method of claim **8**, wherein the quality requirement is comprises a set signal-to-noise-ratio (SNR) requirement over an image bandwidth.

10. The apparatus of claim **1**, wherein the downward-sweeping nonlinear sweep function f(t), as expressed in a frequency-time domain, comprises a function that is equal or less than the smearing error criteria.

11. An apparatus for conducting one or more marine seismic survey, the apparatus comprising:

at least one marine seismic vibrator; and

a vibrator controller for controlling operation of the at least one marine seismic vibrator;

wherein the vibrator controller selects a sweep function based on a smearing error criteria, which, when activated, sweeps the at least one marine seismic vibrator through frequencies according to the sweep function while the at least one marine seismic vibrator is moving.

12. The apparatus of claim **11**, further comprising:

at least one marine streamer having marine seismic sensors; and

a seismic vessel towing the at least one streamer;

wherein when the marine seismic vibrator is activated, the streamer acquires seismic data.

13. The apparatus of claim **12**, further comprising:

a processor configured to process the acquired seismic data to determine properties of an interior section of the Earth.

14. The apparatus of claim **11**, wherein the smearing error criteria comprises a phase error threshold and an amplitude error threshold.

15. A non-transitory computer readable medium having stored thereon instructions that, when executed by a processor, cause the processor to:

control operation of a moving marine seismic vibrator to emit seismic energy according to a sweep function that is based on a smearing error criteria,

wherein the sweep function comprises a downward-sweeping nonlinear sweep function that is based on the smearing error criteria.

16. The computer readable medium of claim **15**, wherein the smearing error criteria comprises a phase error threshold and an amplitude error threshold.

17. The computer readable medium of claim **15**, wherein the downward-sweeping nonlinear sweep function f(t), as expressed in a frequency-time domain, comprises a function that is equal or less than the smearing error criteria.

18. The computer readable medium of claim **15**, wherein the instructions, when executed by the processor, further cause the processor to:

compute smearing errors for each frequency; and

perform desmearing on acquired data for frequencies in which smearing errors are above the smearing error criteria.

19. The computer readable medium of claim **18**, wherein the instructions further cause the processor to perform desmearing on a low frequency end of the acquired data up to 20 Hz.

20. The computer readable medium of claim **15**, wherein the sweep function further comprises a function that is based on a quality requirement.

21. The computer readable medium of claim **20**, wherein the quality requirement comprises a set signal-to-noise-ratio (SNR) requirement over an image bandwidth.

* * * * *